

**SPACE PLASMA ION PROCESSING OF THE LUNAR SOIL: MODELING OF RADIATION-DAMAGED RIM WIDTHS ON LUNAR GRAINS.** S. Chamberlin<sup>1</sup>, R. Christoffersen<sup>2</sup>, and L. Keller<sup>3</sup>, <sup>1</sup>Department of Physics, Utah State University, Logan, UT 84322 (sydney.chamberlin@aggiemail.usu.edu), <sup>2</sup>SAIC, 2450 NASA Parkway, Houston, TX 77058, <sup>3</sup>Mail Code KR, ARES Directorate, NASA Johnson Space Center, Houston, TX 77058.

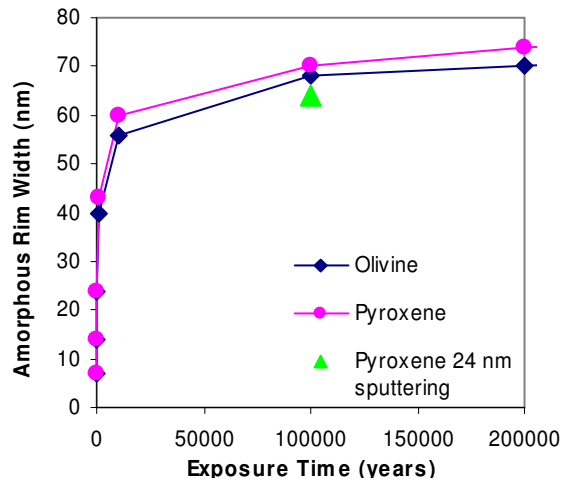
**Introduction:** Chemically and microstructurally complex altered rims around grains in the finest size fraction ( $<20\ \mu\text{m}$ ) of the lunar regolith are the result of multi-stage processes involving both solar ion radiation damage and nanoscale deposition of impact or sputter-derived vapors [1]. The formation of the rims is an important part of the space weathering process, and is closely linked to key changes in optical reflectance and other bulk properties of the lunar surface [2]. Recent application of field-emission scanning transmission electron microscope techniques, including energy dispersive X-ray spectral imaging, is making it easier to unravel the “nano-stratigraphy” of grain rims, and to delineate the portions of rims that represent Radiation-Amorphized (RA) host grain from overlying amorphous material that represents vapor/sputter deposits [2]. For the portion of rims formed by host grain amorphization (henceforth called RA rims), we have been investigating the feasibility of using Monte Carlo-type ion-atom collision models, combined with experimental ion irradiation data, to derive predictive numerical models linking the width of RA rims to the grain’s integrated solar ion radiation exposure time.

**Model Approach:** Several *in-situ* TEM ion irradiation studies have precisely calibrated the critical ion doses associated with ion radiation-induced amorphization in rock-forming silicates [3,4,5]. For total ion energies corresponding to interaction between the ions and target atoms by predominantly nuclear/elastic collisions, silicates typically show abrupt amorphization when the total nuclear/elastic collision energy deposited into a unit volume of crystal reaches a critical level, irrespective of the type or energy of the incident ion [3,4]. The critical deposited energy  $E_d$  for amorphization can serve as a normalizing parameter that allows experimental radiation-induced amorphization data obtained at one set of ion total energies to be used to predict the ion doses for amorphization at other ion energies. The computational tool that allows the two energy regimes to be compared is provided by a Monte Carlo-type ion-atom binary collision code such as SRIM [6]. Because SRIM also provides data for deposited collision energy as a function of depth, it ultimately allows the depth of the amorphous layer in an irradiated target to be calculated as a function of increasing ion dose, as calculated from grain exposure time and time-averaged solar wind ion flux.

**Experimental Inputs:** We determined the critical ion doses and  $E_d$  for amorphization for a pure synthetic enstatite ( $\text{MgSiO}_3$ ) and San Carlos olivine ( $\text{Fo}_{90}$ ) using the *in-situ* IVEM-Tandem TEM ion irradiation facility at Argonne National Laboratory. The details of the irradiation procedures are described in [3,4,7]. For irradiation with 1 MeV Kr ions, an energy regime where nuclear/elastic collisions dominate (similar to lower energy solar wind  $\text{H}^+$  and  $\text{He}^{++}$ ), we determined  $E_d$  (pyroxene) =  $3400\ \text{eV/nm}^3$  and  $E_d$  (olivine) =  $3000\ \text{eV/nm}^3$ . The olivine value is in excellent agreement with previous *in-situ* irradiation studies [3]. The pyroxene value has to our knowledge never been previously determined by *in-situ* irradiation means.

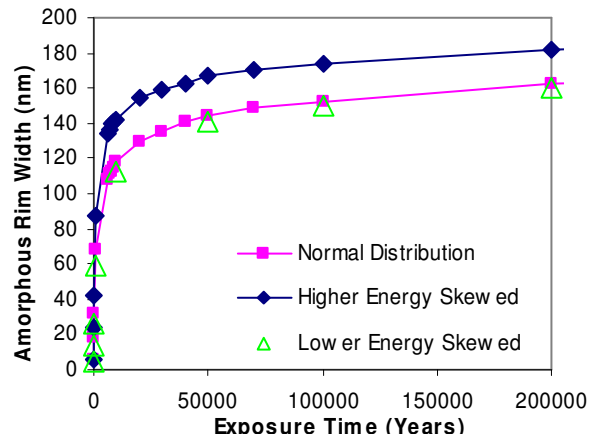
**Model Inputs:** The experimental  $E_d$  values define the critical level of deposited ion collision energy at which pyroxene and olivine become amorphous, independent of the irradiating ion and its energy, as long as ion-atom interactions are in the nuclear stopping regime. Because this requirement holds for ions at typical solar wind energies, our experimental  $E_d$  values are applicable to modeling solar wind radiation damage. Using the SRIM Monte-Carlo code we calculated the combined total nuclear collision energy deposited by solar wind  $\text{H}^+$  and  $\text{He}^{++}$  as a function of depth in pyroxene and olivine for various grain exposure times in the top-most layer of the lunar soil. The  $E_d$  values were used to determine the maximum depth of amorphization for a given exposure time from the corresponding total ion dose and deposited energy versus depth curve. In this approach, one of the main variables is the time-averaged flux versus energy distribution for the solar wind ions. For the current results we used solar wind speed variation data from [8], combined with time-averaged solar wind flux estimates that we have previously made for lunar grains [9]. Other variables include the time-average distribution of ion incidence angles, and the presence or absence of sputtering. For the former we ran SRIM with a plasma-like  $2\pi$  steradian distribution of ion incidence angles. For the latter we simulated sputtering by using SRIM’s ability to incrementally change the starting depth of the incident ion.

**Model Results:** For equivalent solar wind irradiation conditions, olivine and pyroxene have nearly equivalent curves for the growth of their radiation-induced amorphous rims as a function of exposure age



**Figure 1:** Modeled widths of solar ion-amorphized rims on lunar soil grains as a function of exposure time in the top-most layer of the lunar soil. Results are for solar wind speeds narrowly distributed about 450 km/s.

(Fig. 1). The “plateau” feature of the curves is typical and reflects the drop off in deposited energy versus depth as ions reach the end of their range combined with the decrease in solar wind flux at solar wind speeds above the 850 km/sec range (e.g., 3.7 keV  $H^+$  energy). Pyroxene shows slightly higher (~5 nm) plateau values for amorphous rim widths relative to olivine for long exposure times (Fig. 1). This slight difference is unlikely to be detectable in the population of lunar grains given the effect of more important factors such as variable grain exposure times. When sputtering is added to the simulation using lunar sputtering rates suggested by Kerridge [10], 24 nm of surface removal over 100,000 years results in a moderate 9% decrease in the RA rim width (Fig. 1). Overall, sputtering has the net effect of decreasing the total nuclear/elastic energy deposited at a given depth relative to the unsputtered case, extending the exposure times needed to attain the same depth of amorphization. However, our initial results indicate that sputtering rates much higher than those suggested by Kerridge [10] would be needed to produce detectable differences in RA rim widths across a given population of grains. The Figure 1 curves show the growth of amorphous rims for a very narrow solar wind flux versus energy distribution centered around a mean solar wind speed of 450 km/s. Curves for a more realistic set of solar wind speed distributions [8], based on calculations for pyroxene are shown in Figure 2. The plateau values for the rim widths for typical grain exposure times of 5000-150,000 years agree well with typical rim widths measured by TEM [1,2]. This result confirms the reasonableness of the model assumptions and approach, an



**Figure 2:** Modeled widths of solar ion-amorphized rims on pyroxene grains in the lunar soil as a function of exposure time for different solar wind speed distributions.

important first-level goal of the current study. Also shown are changes in the curves that result from moderately skewing the solar ion flux-versus-energy distribution to both lower and higher energies relative to a normal (Gaussian-like) distribution (Fig. 2). Such changes are part of year-to-year and longer timescale variations in solar activity [8]. The growth curves show little change for a negatively skewed distribution largely because of the form of the  $He^{++}$  stopping power curve at lower energies. But this same factor makes the model output sensitive to a positive skew, suggesting that RA rim widths may help identify lunar soil grains exposed during extended periods of higher solar activity, assuming the exposure ages of these grains can be independently estimated.

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**Acknowledgements:** The IVEM-Tandem Facility at Argonne National Laboratory is a national user facility supported by the U.S. Department of Energy. We thank the IVEM-Tandem Facility staff for assistance during the ion irradiations.